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SUMMARY

Simulated radiator surfaces made of arc-textured copper and niobium-one percent-zirconium, and ion beam textured graphite and carbon-carbon composite were fabricated and their integrated spectral emittance characterized from 300 to 3000 K. A thin layer of aluminum oxide, basalt, or iron (III) oxide dust was then deposited on them, and they were subjected to low pressure winds in the Martian Surface Wind Tunnel. It has been found that dust deposited on simulated radiator surfaces may or may not seriously lower their integrated spectral emittance, depending upon the characteristics of the dust. With Al_2O_3 there is no appreciable degradation of emittance on a dusted sample, with basaltic dust there is a 10 - 20 percent degradation, and with Fe_2O_3 a 20 - 40 percent degradation. It was also found that very high winds on dusted highly textured surfaces can result in their abrasion. Degradation in emittance due to abrasion was found to vary with radiator material. Arc-textured copper and Nb-1%Zr was found to be more susceptible to emittance degradation than graphite or carbon-carbon composite. The most abrasion occurred at low angles, peaking at the 22.5° test samples.

INTRODUCTION

Support has been growing over the last few years for a manned mission to Mars which is to take place early in the next century. Because of the distances involved even the first astronauts to reach the surface will probably spend several weeks there. In time, a

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permanent outpost will be established. There will be high power demands compared to present-day spacecraft, and even compared to Space Station Freedom.[1] Nuclear power is the most likely candidate to supply this power, but no matter what the source, heat dissipating radiators will be an important component to any surface power system.

These radiators will have to work in an environment unlike any other they have been used in to date. The atmosphere consists of CO_2 (95.3 percent), N_2 (2.7 percent), Ar (1.6 percent), O_2 (0.13 percent), CO (0.07 percent), H_2O (0.03 percent), and ppm or less of O_3, Ne, Kr, and Xe.[2] There may be reactions between these gases and the hot (1000 K) radiator surfaces. Other potential environmental hazards on Mars include high velocity winds, ultraviolet radiation, rapid temperature changes, dust, reactive soil components, and atmospheric condensates (H_2O and CO_2). Although 99.9 percent of the wind measurements from the Viking landers showed velocities of 20 m/s or less[3], dust storms were observed to move at higher velocities (up to 32 m/s)[4], and aeolian features (sand dunes, etc.) suggest that on occasion wind velocities are substantially higher than that.[5] The surface temperatures range from 135 to 300 K[6], and daily temperature variations of 20 to 50 K are not uncommon.[7]

Another of the possible threats to radiator performance comes from dust suspended either by local dust storms or by the global dust storms which engulf the planet almost yearly. Infrared spectra from the Mariner 9 spacecraft suggested that the dust is a mixture of many minerals including granite, basalt, basaltic glass, obsidian, quartz, andesite, and montmorillonite. The suspended dust particles are quite small, averaging about 2 μm.[8] After a dust storm a significant amount of larger particles may settle out[9] on to radiator surfaces which could lower their emissivity and thus degrade their performance. Tenuous (5 - 8 torr) but high velocity winds may blow the dust off the radiators, and if so, may damage delicate surface structure of the radiators. Perhaps the radiators can be designed to be self-cleaning.

The purpose of this study is to determine how effective aeolian processes on Mars will be in removing the dust from radiator surfaces, and how the shape and orientation of the radiators can affect this process.

METHODS AND MATERIALS

There are several candidate materials for power system radiators. The radiators must have high thermal conductivity, so that heat can be evenly distributed throughout the radiator, and high emittance, so that the heat can be efficiently radiated away. The emittance of any material can be increased dramatically by increasing its surface area. A

promising technology to accomplish this is through microscopically textured surfaces. A technique called arc-texturing can be used to form a textured surface through spot melting and resolidification of the surface with some incorporation of carbon from the arc metal to enhance its emittance by as much as a factor of 14.[10] In this study we tested two oxygen ion-beam textured radiator materials, graphite and carbon-carbon composite, and two arc-textured metals, copper and niobium with one percent zirconium (Nb-1%Zr).

Coupons of each of the four materials were fabricated to be 2.4 cm diameter were made up of each of these four materials. Their untextured thermal emittance was measured using a Perkin-Elmer Lambda-9 spectrophotometer and a Hohlraum reflectometer. The spectrophotometer was used to measure the spectral emittance over wavelengths from 0.4 to 2.5 μm, and the Hohlraum to obtain spectral emittance over wavelengths from 1.5 to 15 μm. The data from both instruments were combined to form a smooth transition from the ultra-violet through infra-red and to allow calculation of the integrated thermal emittance over the temperature range of 300 to 3000 K. The coupons were then arc-textured by manually moving an ac carbon arc discharge, operated in an nitrogen-argon environment, over the surface of the coupon. The technique is described in detail elsewhere.[10] The emittance of the textured coupons was then remeasured. After the wind clearing tests, the emittance of the coupons was measured a third time.

The textured coupons were placed in specially designed sample holders and held in place by a thin metal retaining ring which was secured by means of foil tabs which stretched across three cords of the circle. A spring held them flush with the surface. The sample holders were oriented at tilt angles of 0°, 22.5°, 45°, 67.5°, or 90°. The sample holders could also be oriented horizontally. The sample holders are illustrated in figure 1.

Three types of dust were used to coat the samples. The first dust used was 1800 grit optical grinding powder from American Optical Company. Its principle constituent is aluminum oxide (Al_2O_3), and that is how it will be referred to in this report. This powder did not agglomerate appreciably when exposed to ambient atmospheric moisture, and so gave us the clearest distribution of particles. The second dust was a basalt known as "trap rock". This material is chemically the most similar to the dusts that are found on Mars. The fact that this dust has a grey-green color, however, suggests that there are significant differences. The third dust was iron (III) oxide (Fe_2O_3). Higher oxides of iron have been invoked to explain the Viking biology experiments, and are expected to be present in the dust. The particle size of this material was an order of magnitude smaller than that of the other two samples.

The elemental composition and particle sizes of the three dust types are summarized in table I. However, it should be noted that the purpose of these experiments is not to try to simulate Martian soil, but to try to determine the effects of different dust composition on the dust clearing from the surfaces. Although the values of dust clearing velocities may differ from those determined here, trends in angle and height of the sample from the surface are expected to be similar.

The sample holders were placed in a dusting chamber in which the dust was elevated using dry air and allowed to settle on the samples. Details about the method of dusting and characterization of the dust is described in detail elsewhere.[11] The uniformity and extent of the dust deposition was monitored optically. Optical transmittance measurements were made by sliding the transmittance measuring device over transparent coverslips which were also mounted in the sample holder. Further details about the measurement, as well as dust clearing from the smooth transparent surfaces are reported elsewhere.[12] Only four sample holders could be dusted at a time. The uniformity and extent of the dust deposition, expressed as the ratio of the dusted to the undusted transmittance is shown in figure 2.

The winds on Mars were simulated using the Martian Surface Wind Tunnel (MARSWIT) at NASA Ames Research Center. The MARSWIT is a low pressure (down to a few hundred Pa) wind tunnel 14 m in length with a 1 m by 1.1 m by 1.1 m test section located 5 m from the tunnel's entrance. This flow-through wind tunnel is located within a 4,000 m^3 vacuum chamber. Its characteristics are described in detail elsewhere.[13] The samples were placed in the MARSWIT and tested under the conditions listed in table II.

Winds clearing of Al_2O_3 dust at two different heights from the floor of the wind tunnel were tested. Samples were placed about 2.5 cm from the floor, which should be within the floor's boundary layer, and at about 50 cm, which should be well above it.

RESULTS AND DISCUSSION

Figure 3 shows the emittance as a function of temperature curves for representative samples of each of the radiator materials. The three curves represent the emittance of the pristine material, the emittance of the textured material, and the emittance of the textured material after dusting and exposure in the MARSWIT. Note the large increase in emittance upon texturing the samples, especially in the cases of copper and Nb-1%Zr. The degradation upon exposure in the MARSWIT was strongly dependent upon the wind conditions.

From the wealth of data, three temperatures were selected for evaluation of combined dusting and wind effects on the emittance: a low temperature (300 K), an

intermediate temperature (800 K), and a high temperature (2000 K). It can be surmised from figure 3 that the combined effects of dusting and dust removal diminish as higher temperatures of the samples are characterized for emittance. This trend was born out in the more detailed analysis.

The first series of tests used three of the radiator materials -- arc-textured copper, textured graphite, and textured carbon-carbon composite -- and a single dust material, Al_2O_3. Tests were run at three wind velocities: 55, 85, and 124 m/s. No differences were seen between samples run at the two different heights in the wind tunnel.

Figure 4 shows the effect of the conditions on the 300 K emittance. Figure 4a shows that at wind velocities as high as 55 m/s (123 mph) there is no significant net change in the 300 K emittance (fig. 4a). However, contaminants on surfaces can affect their emissivity. The presence of a dielectric such as Al_2O_3 can greatly enhance the emittance since dielectrics generally have high values of emissivity.[14] This implies that for wind conditions most likely to be found on Mars, even in the sensitive 300 K region, no degradation in performance is expected, provided that the Martian dust behaves similarly to the Al_2O_3 dust.

Even at 85 m/s (190 mph) the 300 K emittance changes are less than 10 percent (fig. 4b). It is interesting to note that there is a differentiation between the copper and the carbon modifications. Arc-textured copper tends to degrade about 10 percent, except at attack angles of 0° and 90°, whereas the graphite and carbon-carbon emittances actually improve by 5 to 10 percent.

At wind speeds of 124 m/s (280 mph) (fig. 4c) this trend is amplified. The carbon-carbon composite shows less than 5 percent degradation; the graphite, up to 20 percent degradation; and the arc-textured copper, as much as 50 percent degradation. This degradation is not what would be expected at first glance. Copper has much higher toughness. One might expect that the wind and embedded dust might fracture the carbon texture off of the copper, but that the copper would survive. Similarly, one might expect the carbon-carbon composite would suffer less damage that the graphite, and indeed it does. Scanning electron microscopy reveals that what in fact is happening is that the arc-textured copper has a layer of graphitic carbon on its surface, and perhaps this is abraded by the wind. Large scale abrasion, however, was not evident from the microscopy.

Figure 5 reveals the same trend in the 800 K emittance, but not as pronounced. Once again there is no appreciable degradation at 55 m/s (fig. 5a). At 85 m/s, there is some enhancement in the carbon-carbon composite and graphite emittances (a few percent), and some degradation (5 - 10 percent) in the arc-textured copper 800 K emittance (fig. 5b). At 124 m/s there is very little degradation in the carbon-carbon composite 800 K emittance

(a few percent), slightly more in the graphite emittance (about 10 percent), but considerably more (20 - 40 percent) in the arc-textured copper 800 K emittance (fig. 5c).

The 2000 K emittance is affected even less (fig. 6). Only the arc-textured copper dusted and exposed to the 124 m/s wind has an emittance degradation greater than 10 percent. Once again the carbon-carbon composite appears to be somewhat more durable than the graphite.

The angular dependence of the degradation is also shown in figures 4, 5, and 6. Note that there is no significant degradation for samples that were held at 0°, even for the 300 K emittance of samples exposed to 124 m/s winds. This implies that radiator surfaces should be built horizontally to the surface to minimize the effects of abrasion. This is supported by the fact that at 0° the dust clearing from photovoltaic surfaces was the lowest.[12] It is clear then that as the wind removes the dust from the surface, surface structures are abraded, and that is what lowers the emittance. The presence of the dust itself seems to have little effect on the emittance, with the important caveat that Martian dust behaves like Al_2O_3.

The composition of the dust seemed to be a critical factor in many of the results. Tests using two additional dust types (basalt and Fe_2O_3) were run in an attempt to resolve the role dust composition plays in radiator performance and its degradation.

It was found that there were differences in the durability of the radiators which depended upon the type of dust used. As mentioned above, the Al_2O_3 interfered very little with the total emittance of the radiator samples. Thus, when the dust was not removed from the samples their emittance was essentially unchanged from the clean samples. However, when the basalt dust remained on the samples, their emittance was lowered by 10 - 20 percent. The Fe_2O_3 caused even more degradation. Unremoved Fe_2O_3 dust lowered radiator emittance by 20 - 40 percent. The Fe_2O_3 also appears to be more abrasive. For example, the degradation of the emittance from a 95 m/s wind on a Fe_2O_3 dusted surface was comparable to that of a 124 m/s wind dusted with Al_2O_3. This is surprising when one compared the hardness of Al_2O_3 ($\approx$ 9 Moh) with that of Fe_2O_3 ($\approx$ 6 Moh). Particle size may play a key role here.

It is instructive to plot the change in the emittance of surfaces as a function of wind velocity at a given angle. Figure 7 shows such a plot for the 300 K emittance of samples inclined at 45° for wind velocities ranging from 31 to 124 m/s. The 31 and 42 m/s samples were initially dusted with basalt, and some of the 85 and the 95 m/s samples were initially dusted with Fe_2O_3, the rest were dusted with Al_2O_3. The trend, regardless of the dust, is similar. At low wind velocities, below the dust clearing threshold, the emittance is strongly

affected by the properties of the dust. In the case of basalt (see fig. 7) the emittance is significantly degraded, whereas in the case of the Al_2O_3 (see the 0° data of fig. 4a) it is not. At high wind velocities the emittance drops. The most likely explanation for this is abrasion, however, there were no obvious differences observed using a scanning electron microscope. The arc-textured samples were degraded much more than the ion-beam textured, consistent with abrasion of the high emittance carbon surfaces which cover the metals.

By observing the way that dust is cleared from smooth surfaces under these same conditions it has been found that there are two mechanisms of dust removal.[15] At low angles (22.5° and less) the dust is rolled off of the surface. At greater angles (45° and higher) the dust is aerodynamically lifted from the surface. One would expect that the rolling dust removal mechanism would be more abrasive than the aerodynamic lift mechanism. If this were the case one would expect that the degradation in emittance would peak at 22.5° instead of the 45° which was determined to be the maximum for dust removal using optical transmittance in a related study.[12] From figures 4c, 5c, and 6c (the 124 m/s data) we see that this is may indeed be the case.

CONCLUSIONS

It has been found that dust deposited on simulated radiator surfaces may seriously lower their integrated spectral emittance, depending upon the characteristics of the dust. With Al_2O_3 there is no appreciable degradation of emittance on a dusted sample, while with basaltic dust there is a 10 - 20 percent degradation, and with Fe_2O_3 a 20 - 40 percent degradation. The basalt matches the elemental composition of the Martian surface best, and so may be the best match to Martian dust, but the color of the basalt used in the tests is green, so there are obviously differences in the optical properties.

A large difference in the effects of dust and abrasion on the emittance was found which depends upon the emittance temperature of the radiator. The 300 K emittance degradation was about twice that of the 2000 K emittance changes for the same sample. Thus, hotter running radiators can be expected to be affected less by dust and abrasion than cooler running ones.

It was also found that very high winds on dusted highly textured surfaces can result in their abrasion. Abrasion was found to vary with radiator material. Arc-textured copper and Nb-1%Zr was found to be more susceptible to emittance degradation by such abrasion than graphite or carbon-carbon composite. The most abrasion occurred at low angles, peaking at the 22.5° test samples. This is probably due to the dominance of particles rolling

off of the surface at low angles as opposed to the aerodynamic lift mechanisms which dominate at high angles.

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Table I -- Composition of Dusts

	Viking	Percent by Weight Opt Grit	Basalt	Fe_2O_3
SiO_2	44.7	6.6	46.6	0
Fe_2O_3	18.1	0.6	13.0	100
MgO	8.3	0.0	6.1	0
Al_2O_3	5.7	89.0	16.6	0
CaO	5.6	0.0	11.1	0
TiO_2	0.9	3.0	2.0	0
Cr_2O_3	0.0	0.6	0.0	0
Na_2O	?	0.0	2.3	0
K_2O	0.0	0.0	1.1	0
MnO	0.0	0.0	0.3	0
CO_2	?	0.0	0.1	0
P_2O_5	0.0	0.0	0.1	0
size, μm		7-25	5-20	.5-2.5

Table II -- Wind Conditions Within the MARSWIT

Velocity	Stat Pres	Dyn Pres	Temp	Time	Dust
10 m/s	1000 Pa	1.2 Pa	290 K	600 sec	Al_2O_3
23	1000	6.3	290	600	Al_2O_3
30	1000	10.7	290	600	Al_2O_3
30	1000	10.9	285	300	Fe_2O_3
31	1000	11.4	290	900	Al_2O_3
31	850	9.9	285	600	Basalt
35	1000	14.5	290	300	Al_2O_3
42	950	20	285	600	Basalt
50	1000	30	285	90	Fe_2O_3
55	1000	36	290	120	Al_2O_3
60	1000	43	285	600	Fe_2O_3
85	1000	86	290	30	Al_2O_3
85	900	78	285	600	Fe_2O_3
95	1200	131	285	600	Fe_2O_3
124	1000	182	290	45	Al_2O_3

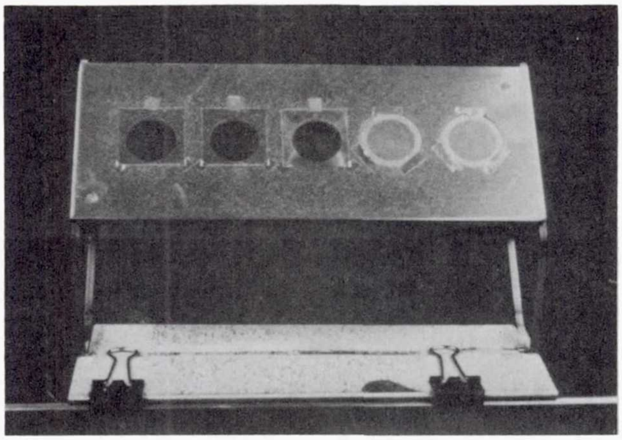

Figure 1.—Sample holder designed to test aeolian dust removal from photovoltaic and radiator surfaces.

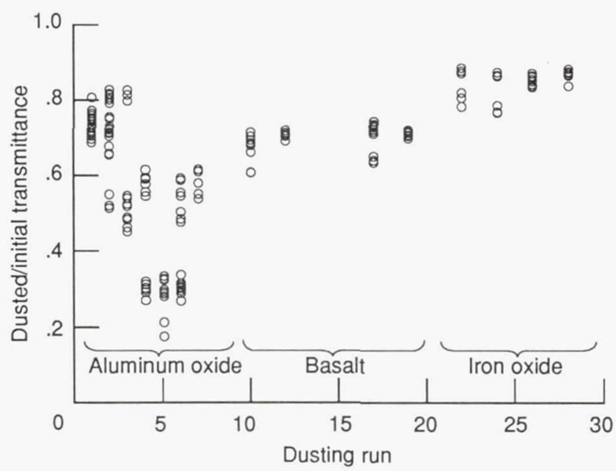

Figure 2.—Uniformity of dust deposition.

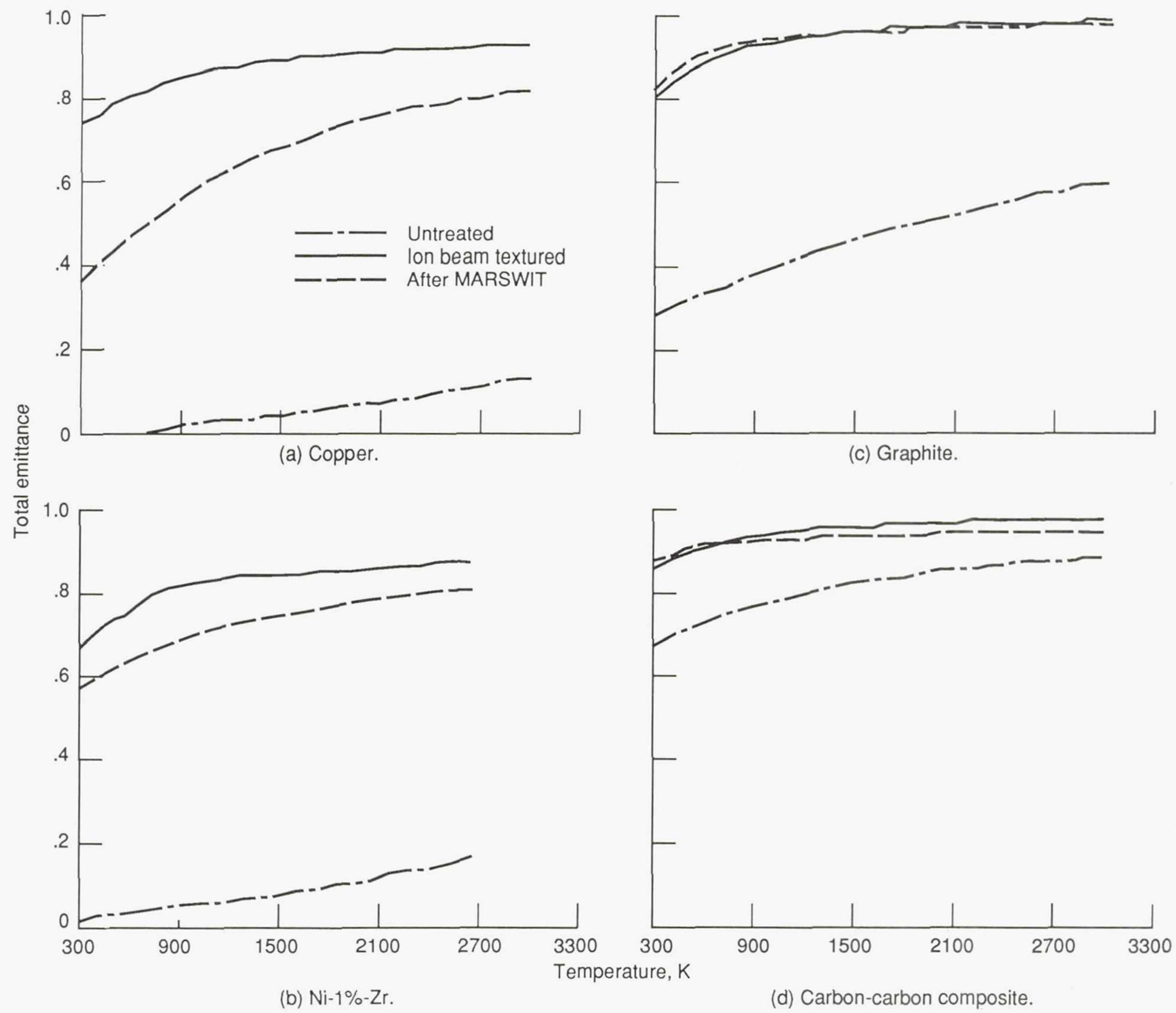

Figure 3.—Total emittance as a function of temperature for selector radiator materials.

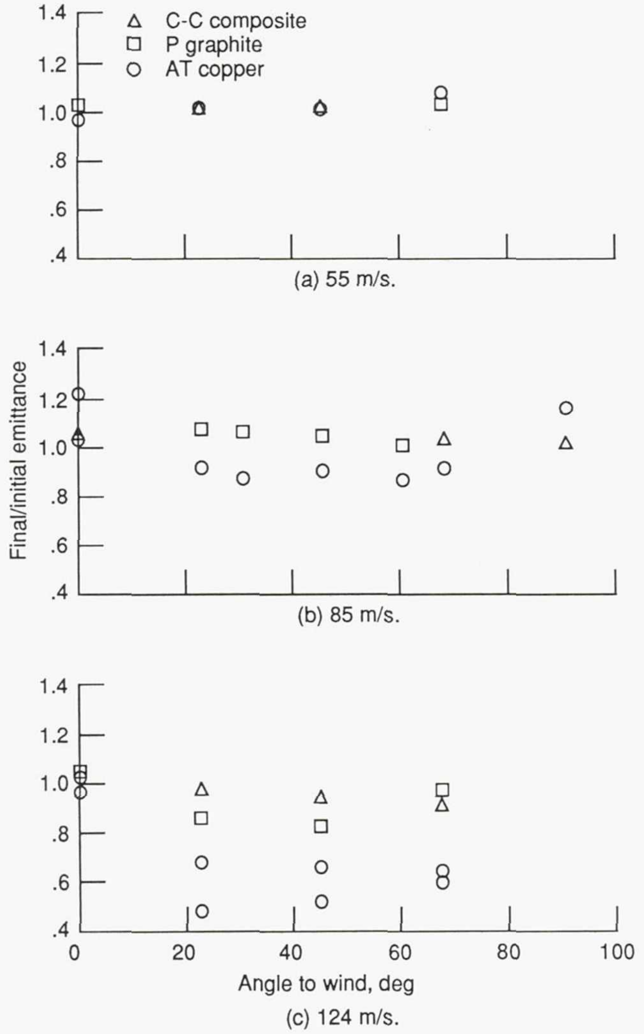

Figure 4.—Changes in the 300 K emittance when predusted samples are exposed to 1000 Pa static pressure winds.

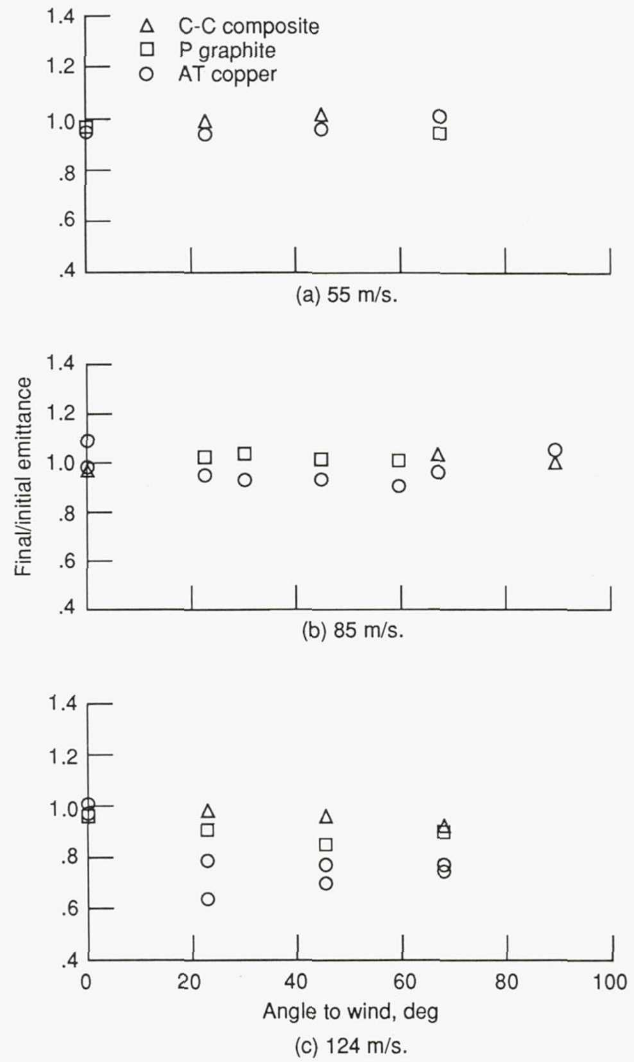

Figure 5.—Changes in the 800 K emittance when predusted samples are exposed to 1000 Pa static pressure winds.

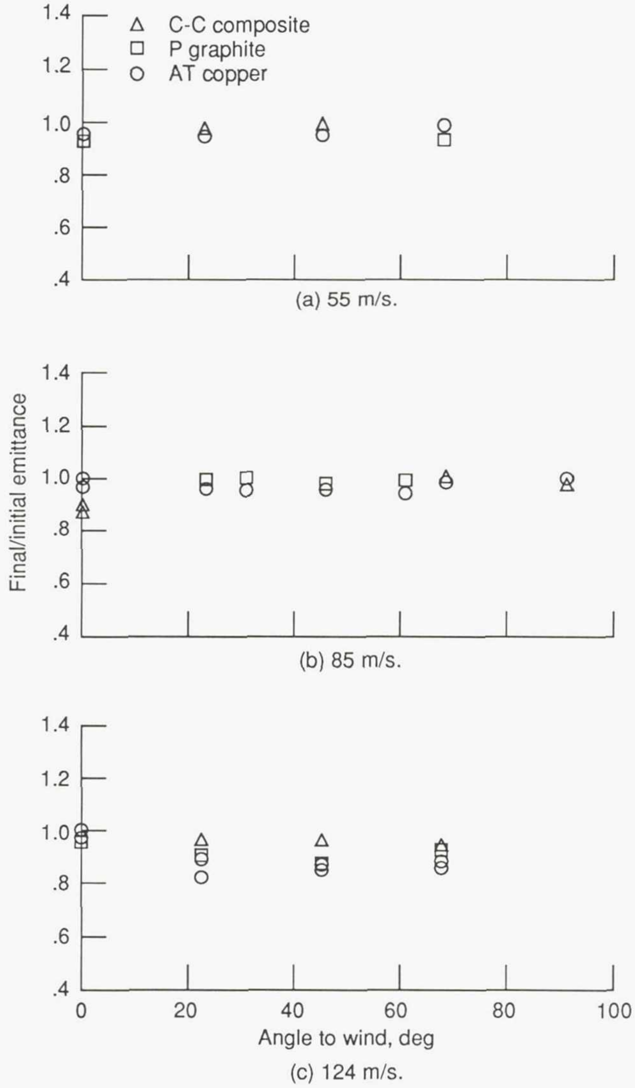

Figure 6.—Changes in the 2000 K emittance when predusted samples are exposed to 1000 Pa static pressure winds.

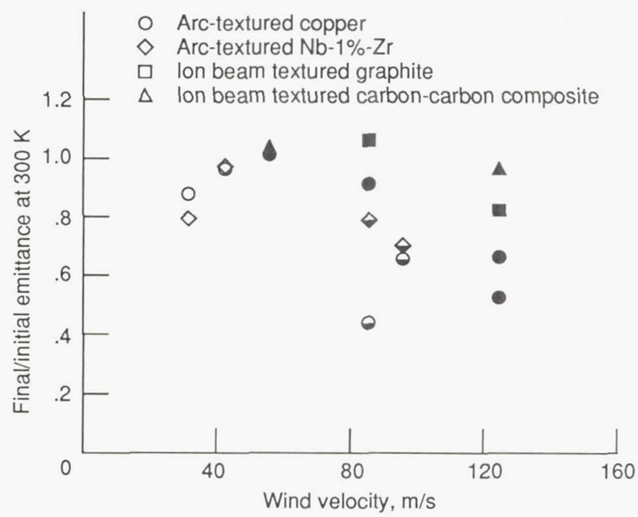

Figure 7.—Degradation of predusted textured radiator surfaces when exposed to 100 Pa static pressure winds. Filled symbols denote Al_2O_3 dust, open symbols denote basalt dust, half-filled symbols denote Fe_2O_3 dust.

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16. Abstract

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